

**REMARKS**

This Preliminary Amendment cancels original claims 1 to 7 in the underlying PCT Application No. PCT/EP2005/050177 and adds new claims 8 to 13. The new claims conform the claims to the U.S. Patent and Trademark Office rules and do not add new matter to the application.

In accordance with 37 C.F.R. § 1.125, the Substitute Specification (including the Abstract, but without the claims) contains no new matter. The amendments reflected in the Substitute Specification (including the Title and Abstract) are to conform the Specification and Abstract to U.S. Patent and Trademark Office rules or to correct informalities. As required by 37 C.F.R. § 1.121 and § 1.125, a Marked Up Version Of The Substitute Specification comparing the Specification of record and the Substitute Specification also accompanies this Preliminary Amendment. In the Marked Up Version, underlining indicates added text and "strike-throughs" and double-brackets indicate deleted text. Approval and entry of the Substitute Specification (including Abstract) are respectfully requested.

Also enclosed are translated copies of the International Search Report and the International Preliminary Examination Report. The Search Report includes a list of documents that were considered by the Examiner in the underlying PCT application.

It is asserted that the subject matter of the present application is new, non-obvious, and useful. Prompt consideration and allowance of the application are respectfully requested.

Respectfully Submitted,

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Dated: 7/14/2006

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METHOD AND COMPUTER PROGRAM FOR GENERATING A MODEL FOR THE RESPONSE  
OF A CONTROL DEVICE

FIELD OF THE INVENTION

The present invention relates to a method for generating a model for the functional response of a control device, the control device being ~~designed~~ for calculating a suitable manipulated variable for a controlled system, in particular an air path system of an internal combustion engine, in response to a preselected setpoint value for a controlled variable of the controlled system. In addition, the present invention relates to a control system and a regulating system, each having a control device designed in this way. Finally, the present invention also relates to a data medium having the aforementioned computer program.

~~Background Information~~

BACKGROUND INFORMATION

The publication "Path and Articulation Regulating Algorithms for the 'Modular robot'," Martin Sundin, 1993, describes a linear regulating model which solves for manipulated variable  $r_s$  according to equation 4.3.3, starting from a linear differential equation according to equation 3.2.1.

Such a method and such systems are essentially ~~known from~~ discussed in the ~~related art~~, in particular International Patent Application WO 89/09953. This ~~describes~~ discusses a method for tracking the trajectory of axial positions of a robot. It is assumed here that the controlled system is linear and may be described with the help of a transfer function  $G(s)$  in the frequency range.

A manipulated variable for the controlled system is determined from the trajectory sequence, i.e., the preselected setpoint characteristic of the axial motion, with the help of a control device whose transfer function corresponds to the inverse transfer function of the controlled system. To be able to set the controlled variable even more precisely at the predetermined setpoint characteristic, the manipulated variable is corrected, if necessary, with the help of a regulating device connected in parallel with the control device. To this end, the regulating device receives as a controlled variable a control deviation between a setpoint position and an actual axial position. The regulating device calculates from this control deviation a correction factor for the manipulated variable, this correction factor being applied to the manipulated variable calculated by the control device to then provide the controlled system with a corrected manipulated variable generated in this way.

The method ~~described in~~ of WO 89/09953 has the disadvantage that it is applicable only to controlled systems having a linear response and having only a single controlled variable.

## SUMMARY OF THE INVENTION

Against the background of ~~this related art,~~ the foregoing, an object of the present invention is therefore to provide a method and a computer program for generating a model for the functional response of a control device as well as a control system and a regulating system, each having a control device having a model generated in this way and a data medium having the aforementioned computer program, which allow such a model to be generated for a control device even when the response of a controlled system downstream from the control device is not linear and multiple controlled variables are to be controlled and/or regulated.

This object is achieved by the method ~~as recited in Patent Claim 1,~~ described herein. This method is characterized in that inversion

of the model for the controlled system for generating the model for the control device includes the following steps: calculating an equation for the  $N^{\text{th}}$  derivation of the controlled variable as a function of the manipulated variable and the controlled variable itself and/or its derivatives of the  $n^{\text{th}}$  order with respect to time, where  $n = 1, \dots, N-1$ ; and generating the model for the control device by solving the equation for the  $N^{\text{th}}$  derivatives of the controlled variable for the manipulated variable.

## ~~Advantages of the Invention~~

~~This~~The exemplary method according to the present invention offers the advantage ~~that it is possible with this method to generate of~~generating a model for a control device within a control system or a regulating system even when the particular controlled system in these systems has a nonlinear response and/or multiple controlled variables are to be controlled or regulated. In any case, however, the prerequisite is that the controlled system must be describable in the form of a mathematical model using physically motivated equations. The model generated according to the exemplary embodiment and/or exemplary method of the present invention for the control device is then valid in the entire range of operation of the controlled system mapped by the model.

In application of the exemplary method according to the present invention, it is advantageously not usually necessary for the model for the controlled system to describe its functional response to the full extent and in great detail. Instead, for the exemplary embodiment and/or exemplary method of the present invention it is sufficient to use a model of the controlled system that has possibly been reduced and maps its dynamics and linear and/or nonlinear response only inasmuch as this is relevant for the regulating operation.

An exemplary embodiment of the generation of a model for the control device according to the present invention is the subject matter of a subclaim.

The object defined above is also achieved by a computer program for performing the method, by a data medium having this computer program and by a control system and a regulating system, each having a control device having the model generated according to the exemplary embodiment and/or exemplary method of the present invention. The advantages of these approaches correspond to the advantages mentioned above with respect to the method claimed.

In addition, a regulating device provided in the regulating system advantageously results in an additional precisation, i.e., correction of the manipulated variable, so that with the help of this regulating device, the controlled variable may be adjusted even more precisely to the particular predetermined setpoint value. When using a control device having the model generated according to the exemplary embodiment and/or exemplary method of the present invention, this regulating device need only correct minor deviations in the controlled variable from the setpoint value and/or a predetermined setpoint trajectory; it is therefore not excessively burdened in particular in comparison with known regulating devices based on engine characteristics maps, and therefore this device is very robust.

Since the model is valid in the entire operating range of the controlled system -- at least as a rule -- only the particular regulator parameters need be adjusted once for the entire operating range of the controlled system in the case of the regulating device. When using the model generated according to the exemplary embodiment and/or exemplary method of the present invention for the control device, it is not necessary to constantly adapt the regulator parameters to the ever-changing operating points of the controlled system.

#### Drawing

~~The description is accompanied by a total of three figures.~~

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a control system according to an exemplary embodiment of the present invention.

Figure 2 shows ~~the~~ an exemplary method according to the present invention; ~~and~~.

Figure 3 shows a regulating system according to an exemplary embodiment of the present invention.

#### DETAILED DESCRIPTION

~~Description~~The exemplary embodiment and/or exemplary method of the  
5 ~~Exemplary Embodiments~~The present invention is explained in greater detail below in the form of exemplary embodiments with reference to the figures cited above.

Figure 1 shows a control system 100 for controlling a controlled variable  $y$ . This control system 100 includes a setpoint value  
10 preselecting device 110 for preselecting at least one setpoint value  $y_d$  for controlled variable  $y$ , in particular in the form of a trajectory sequence. In the example illustrated in Figure 1, setpoint value preselecting device 110 generates  $n + 1$  setpoint values in the form of a setpoint value  $y_d$  and its first through  $n^{\text{th}}$   
15 derivatives with respect to time.

In addition, control system 100 includes a control device 120 for converting these setpoint values into at least one manipulated variable  $u_d$ . Manipulated variable  $u_d$  is used as an input variable for a controlled system 130 for controlling controlled variable  
20  $y$  at the output of the controlled system.

Manipulated variable  $u_d$  is to be dimensioned by control device 120 so that controlled variable  $y$  at the output of controlled system 130 is set at setpoint value  $y_d$  output by setpoint value preselecting device 110. To do so, it is necessary for control  
25 device 120 to be designed suitably. This suitable design of control device 120 is the subject matter of the exemplary embodiment and/or exemplary method of the present invention and is described in detail below.

Figure 2 shows the individual method steps for generating a  
30 suitable mathematical model for describing the functional response of control device 120 in detail. It is assumed here that a

mathematical model in the form of physical model equations is known for controlled system 130. These model equations for controlled system 130 ~~preferably~~may include only the dynamic effects that are critical for the regulating operation. As a rule, the model equations are obtained from conservation laws, i.e., axioms, and are typically representable in the following form:

$$\dot{x} = f(x,u), \quad x(0) = x_0 \in \mathbb{R}^n, \quad u \in \mathbb{R}^m \quad (1)$$

where

- x represents a state vector, ~~preferably including~~which may include only the state variables required from a regulating standpoint;
- u represents a manipulated vector which includes at least one manipulated variable;
- f represents any mathematical function, in particular a differential equation;
- $x_i(0)$  represents a state variable at point in time  $t = 0$ ; and
- $x_0$  represents an initial value.

All state variables  $x_i$  as factors of the state vector as well as all manipulated variables  $u$  are essentially time-dependent variables.

The method according to the present invention for calculating a mathematical model for control device 120 is to be explained in greater detail below on the example of the control and/or regulation of a controlled system 130 having nonlinear response. This system may be, for example, a mass moved by an electric motor. The response of this regulated system may be represented by the following nonlinear differential equation system:

$$\dot{x}_1 = x_2 \quad (2a)$$

$$\dot{x}_2 = -x_1^2 - x_2 + x_3 \quad (2b)$$



$$\dot{x}_3 = -ax_3 - x_2 + u_d \quad (2c)$$

In this differential system, a state vector  $x$  having three state variables  $x_1$ ,  $x_2$  and  $x_3$  is used to describe the functional response of the controlled system. Due to the use of three state variables, the controlled system may also be called a third-order system. For the aforementioned controlled system, state variable  $x_1$  represents the distance traveled by the mass, state variable  $x_2$  represents the velocity of the mass and state variable  $x_3$  represents the current in the electric motor. Parameter  $a$  in equation (2c) is a model parameter. This controlled system also includes a nonlinear spring described by the quadratic term in equation (2b). All states  $x_i$ , where  $i = 1, \dots, N = 3$ , as well as parameter  $a$  and manipulated variable  $u$  are standardized and therefore dimensionless.

The method according to the present invention is explained in greater detail below on the example of the calculation of a model for a control device which is adapted to a controlled system having the functional response described in equations (2a)-(2c).

First, as shown in Figure 2, state variable  $x_i$  to be regulated is selected from the factors of state vector  $x$ . For example, state variable  $x_1$ , i.e., the distance traveled by the mass, is selected here as controlled variable  $y$ . This choice is described mathematically by the following simple equation (3):

$$y = x_1 \quad (3)$$

In the following, the method according to the present invention as shown in Figure 2 provides for the first  $N$  derivatives  $\left( \dot{y}, \ddot{y}, \dots, y^{(N)} \right)$  of controlled variable  $y$  to be formed.

Thus the first, second, and third derivatives are formed in the concrete example mentioned above having a controlled system of the third order,  $N = 3$ . These are calculated taking account

differential equations (2a), (2b) and (2c) of the model of controlled system 130 as follows:

$$y = x_1 \quad (3)$$

$$\dot{y} = \dot{x}_1 = x_2 \quad (4)$$

$$5 \quad \ddot{y} = \ddot{x}_2 = -x_1^2 - x_2 + x_3 \quad (5)$$

$$\begin{aligned} \ddot{y} = \ddot{x}_2 &= -2x_1\dot{x}_1 - \dot{x}_2 + \dot{x}_3 \\ &= -2x_1x_2 - (-x_1^2 - x_2 + x_3) + (-ax_3 - x_2 + u_d) \\ &= x_1^2 - 2x_1x_2 + (1-a)x_3 + u_d \end{aligned} \quad (6)$$

Equations (3), (4) and (5) represent an equation system having three equations and three state variables  $x_1$ ,  $x_2$  and  $x_3$ . In the method according to the present invention, this equation system is used to calculate state vector  $x = [x_1, x_2, x_3]^T$ . Individual state variables  $x_i$ , where  $i = 1-3$ , as factors of this state vector are calculated by solving this equation system. For the example here, state vector  $x$  is calculated by the procedure described here as follows:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} y \\ \dot{y} \\ y^2 + \dot{y} + \ddot{y} \end{bmatrix} \quad (7)$$

Individual state variables  $x_i$  in the representation according to equation (7) are advantageously represented as a mathematical function of only controlled variable  $y$  and/or its derivatives with respect to time  $\left(\dot{y}, \ddot{y}, \dots, y^{(N)}\right)$ .

In general, the method according to the present invention then provides for any state variables  $x_i$  that might be present in the  $N^{\text{th}}$  derivative  $y^{(N)}$  of controlled variable  $y$  to be replaced by their equivalent representations as a function of controlled variable

y or their derivatives with respect to time according to equation (7).

When applying this procedure to the example, a corresponding replacement must also be made in the  $N = 3^{\text{rd}}$  derivative of the controlled variable according to equation (6). Equation (6) is then rewritten as follows, taking into account equation (7):

$$\ddot{y} = u_d - \dot{y} - 2y\dot{y} - \ddot{y} - a(y^2 + \dot{y} + \ddot{y}) \quad (8)$$

Solving equation (8) for manipulated variable u results directly in the model being sought for control device 120 when controlled system 130 to be controlled exhibits the functional response described by equations (2a), (2b) and (2c). The mathematical model for control device 120 then describes manipulated variable u as the output variable of control device 120 in functional dependence on its input variables, i.e., the predetermined setpoint values for controlled variable y. The model for the control device may then be represented as follows for the controlled system mentioned as an example:

$$u_d = \dot{y} + \ddot{y} + \ddot{\ddot{y}} + 2\dot{y}y + a(\dot{y} + \ddot{y} + y^2) \quad (9)$$

As a model of the control device, equation (9) represents an inversion of the model of controlled system 130 in the form  $u_d = f(y)$ , which is typically represented in the form  $y = g(u_d)$ ; see equations (3) through (6).

The controlled system described here by equations (2a), (2b) and (2c) as an example in the form of a mass moved by an electric motor merely illustrates the method according to the present invention. Essentially the method according to the present invention may be applied to any type of controlled systems whose functional response is describable by physically motivated model equations, including nonlinear equations. This is also true in particular of an air path system of an internal combustion engine as a controlled system.

Additionally or alternatively to the air path system, in particular by regulating the charging pressure, exhaust gas recycling and filling as well as lambda regulation, any other function in the area of engine management may also be selected as the controlled system. This would include, for example, the injection system, in particular with rail pressure regulation, pressure wave compensation, cylinder pressure regulation and combustion start regulation, engine speed regulation with idling regulation in particular, bucking and load impact attenuation or torque regulation. When using the air path system as the controlled system, such a controlled system may be simulated by suitably selected model equations using the state variables of intake manifold pressure, air mass in the intake manifold, and air temperature in the intake manifold. The method according to the present invention for calculating a suitable model for a control device is also applicable in particular for a model of such a controlled system.

Additional and/or more extensive stabilization of the controlled system from the standpoint of the predetermined setpoint value and/or the predetermined trajectory sequence is implementable by a regulating device 150 connected in parallel with control device 120, as illustrated in Figure 3. The regulating system illustrated in Figure 3 is based on the control system illustrated in Figure 1, where the functional response of control device 120 is described by a mathematical model which ~~has~~may have been generated ~~preferably~~ according to the present invention. In addition to control system 100, the regulating system according to Figure 3, however, additionally includes this regulating device 150. This may be any regulator, e.g., a PIDT<sub>1</sub> regulator. A control deviation e between controlled variable y at the output of controlled system 130 and predetermined setpoint value y<sub>d</sub> for the controlled variable are sent as input variables to this regulator. Mathematically, control deviation e is calculated as follows:

$$e(t) = y_d(t) - y(t) \quad (10)$$

Regulating device 150 then generates suitable correction factors for manipulated variable  $u$  in accordance with control deviation  $e$ , taking into account its regulator parameters  $K_p$ ,  $K_I$ ,  $K_D$  and/or  $T_I$ . A proportional correction factor  $u_p$  for manipulated variable  $u$  is calculated as follows:

$$u_p = K_p e \quad (11)$$

where

$K_p$  represents the regulator parameter for the proportional correction factor.

10 An integral regulator factor  $u_I$  is typically calculated as follows:

$$u_I = K_I \int_0^t e(\tau) d\tau, \quad u_I(0) = u_I^0 \quad (12)$$

where

$K_I$  represents the regulator parameter for the integral correction factor; and

15  $u_I^0$  represents an initial value for the integral regulating factor.

If regulating device 150 additionally includes a differential regulating factor, it is typically calculated as follows:

$$T_I \dot{u}_D + u_D = K_D \dot{e}, \quad u_D(0) = u_D^0 \quad (13)$$

20 where

$K_D$  represents the regulator parameter for the differential regulating factor; and

$u_D^0$  represents an initial value for the differential regulating factor.

If regulating device 150 actually includes both a proportional factor as well as an integral and differential factor, then correction factor  $u_{ctrl}$  for manipulated variable  $u$  is calculated as the sum of these factors as follows:

$$5 \quad u_{ctrl} = u_p + u_I + u_D \quad (14)$$

where

$u_p$  represents the proportional regulating factor;

$u_I$  represents the integral regulating factor; and

$u_D$  represents the differential regulating factor.

10 Total correction factor  $u_{ctrl}$  of manipulated variable  $u$  calculated in this way is then added with the help of an addition or subtraction device 140 to manipulated variable  $u_d$  calculated by control device 120 to finally obtain a resulting corrected manipulated variable  $u$  from this addition. The corrected manipulated variable causes  
15 an even more precise adjustment of controlled variable  $y$  to setpoint quantity  $y_D$  in contrast with the manipulated variable supplied by control device 120.

The method according to the present invention ~~is preferably~~ may be implemented in the form of a computer program. The computer program  
20 may, if necessary, be saved together with other computer programs on a computer-readable data medium. The data medium may be a diskette, a compact disk, a flash memory or the like. The computer program saved on the data medium may then be transferred or sold as a product to a customer. As an alternative to transfer via data  
25 media, transfer of the computer program over an electronic communications network, in particular the Internet, ~~is~~ may also possible be done.

~~Abstract~~ ABSTRACT OF THE DISCLOSURE

A method and a computer program for generating a model for the functional response of a control device ~~(120)~~, for generating a manipulated variable ~~( $u_a$ )~~ for a controlled system ~~(130)~~ in response to a preselected setpoint value ~~( $y_a$ )~~ is described. The model is also generated for nonlinear controlled systems ~~(130)~~ by performing the following steps: calculating the  $N^{\text{th}}$  derivative of the controlled variable as a function of the manipulated variable and of the controlled variable ~~( $y$ )~~ itself and/or its derivatives of the  $n^{\text{th}}$  order with respect to time and generating the model for the control device ~~(120)~~ by solving the  $N^{\text{th}}$  derivative of the controlled variable ~~( $y$ )~~ for the manipulated variable ~~( $u_a$ )~~. ~~Figure 1.~~

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